SPICA and the Promise of the Far-Infrared

Matt Bradford (JPL)

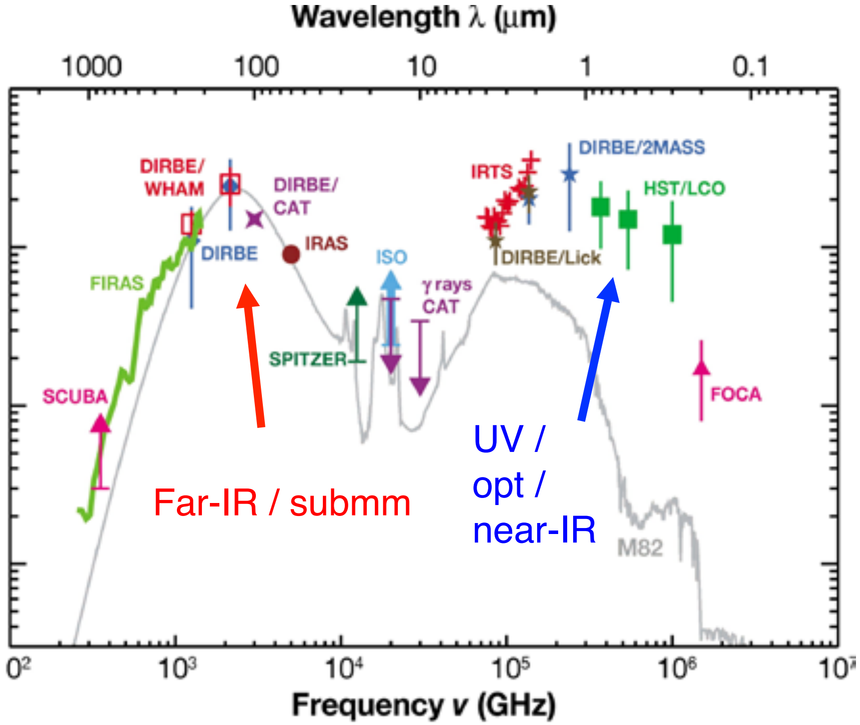
22 September 2011

NASA COPAG Workshop

Spitzer GOODS - 24 μm; Daddi et al.

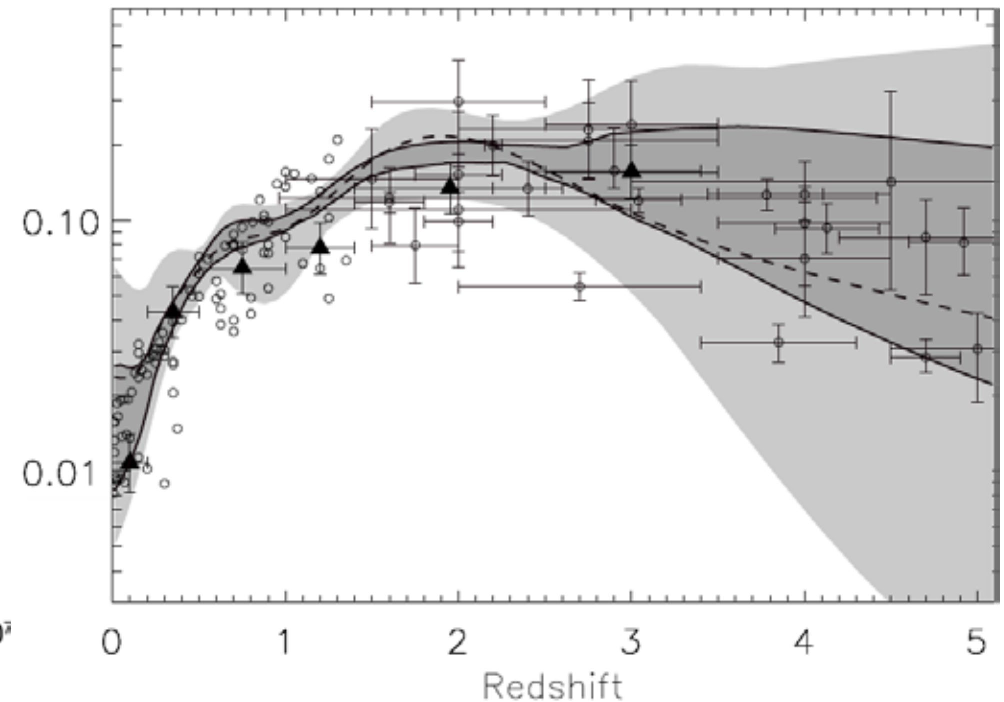
The Infrared Background & Dusty Star-Forming Galaxies

Integrated star & AGN light: FIR is half



Lagache, Puget & Dole (2005), ARAA 43

Star formation history



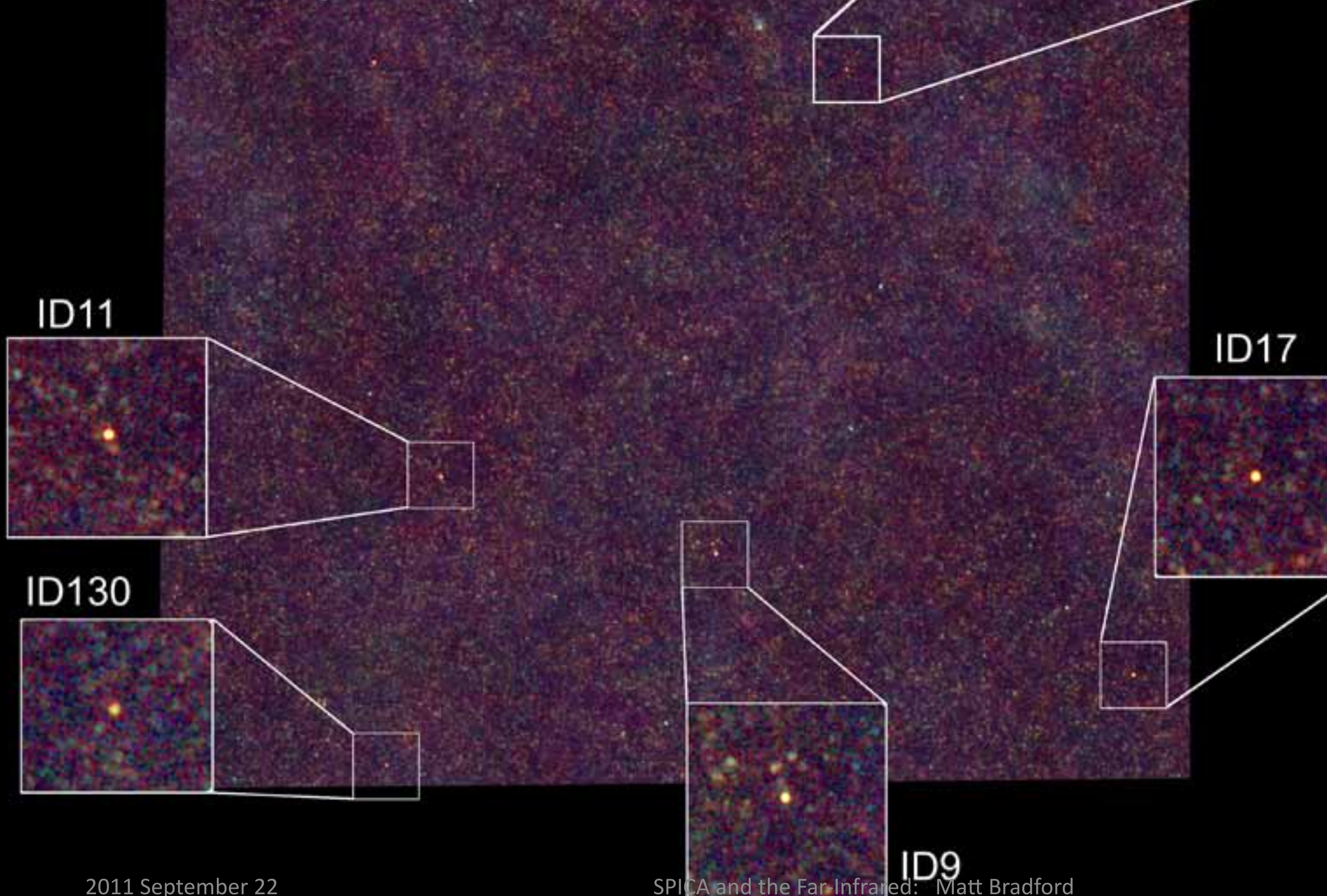
Le Borgne et al., 2009, shaded region
points from Hopkins & Beacom 2006

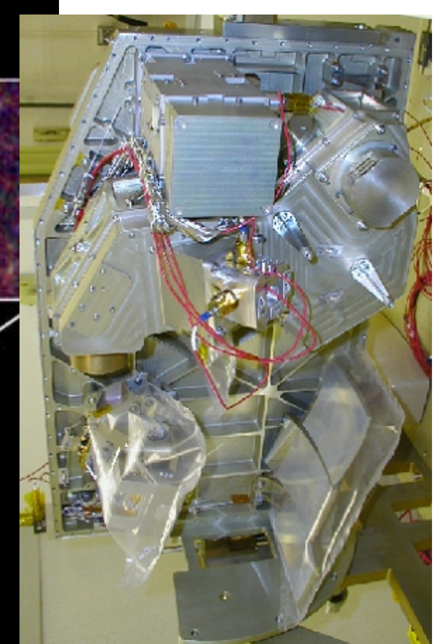
Submillimeter / millimeter wavelengths probe the interesting early star-formation phase.

- Greatest uncertainty at high redshift.
- Reionization between z=11 and z=6 (0.4 to 1.0 Gyr).

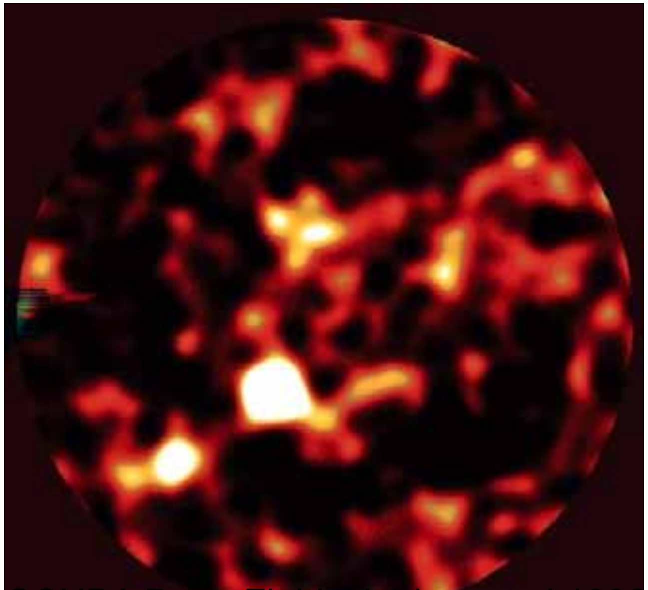
Herschel SPIRE Far-IR Surveys

Caltech / JPL Bolometers at the heart of SPIRE (used at CSO)
200, 350, 500 microns
hundreds of square degrees, hundreds of thousands of sources
most likely from the first half of the Universe's history
H-ATLAS: http://www.h-atlas.org/
More coming from ground-based surveys: SCUBA-2, SPT, ACT

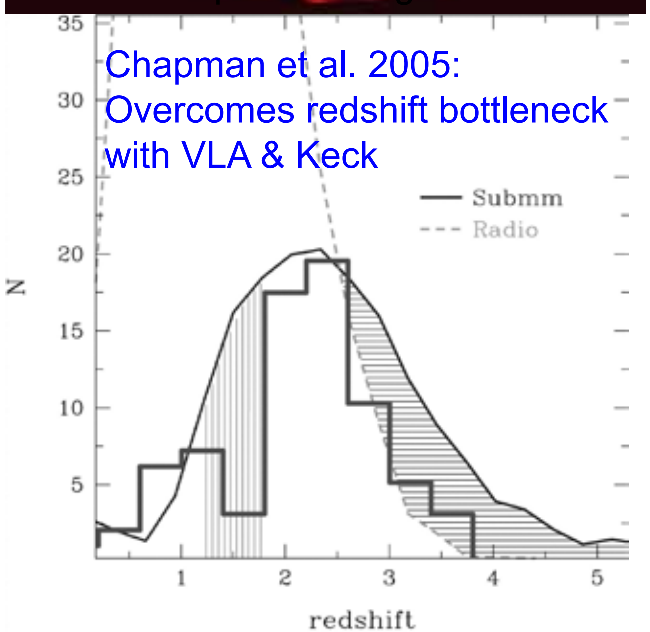


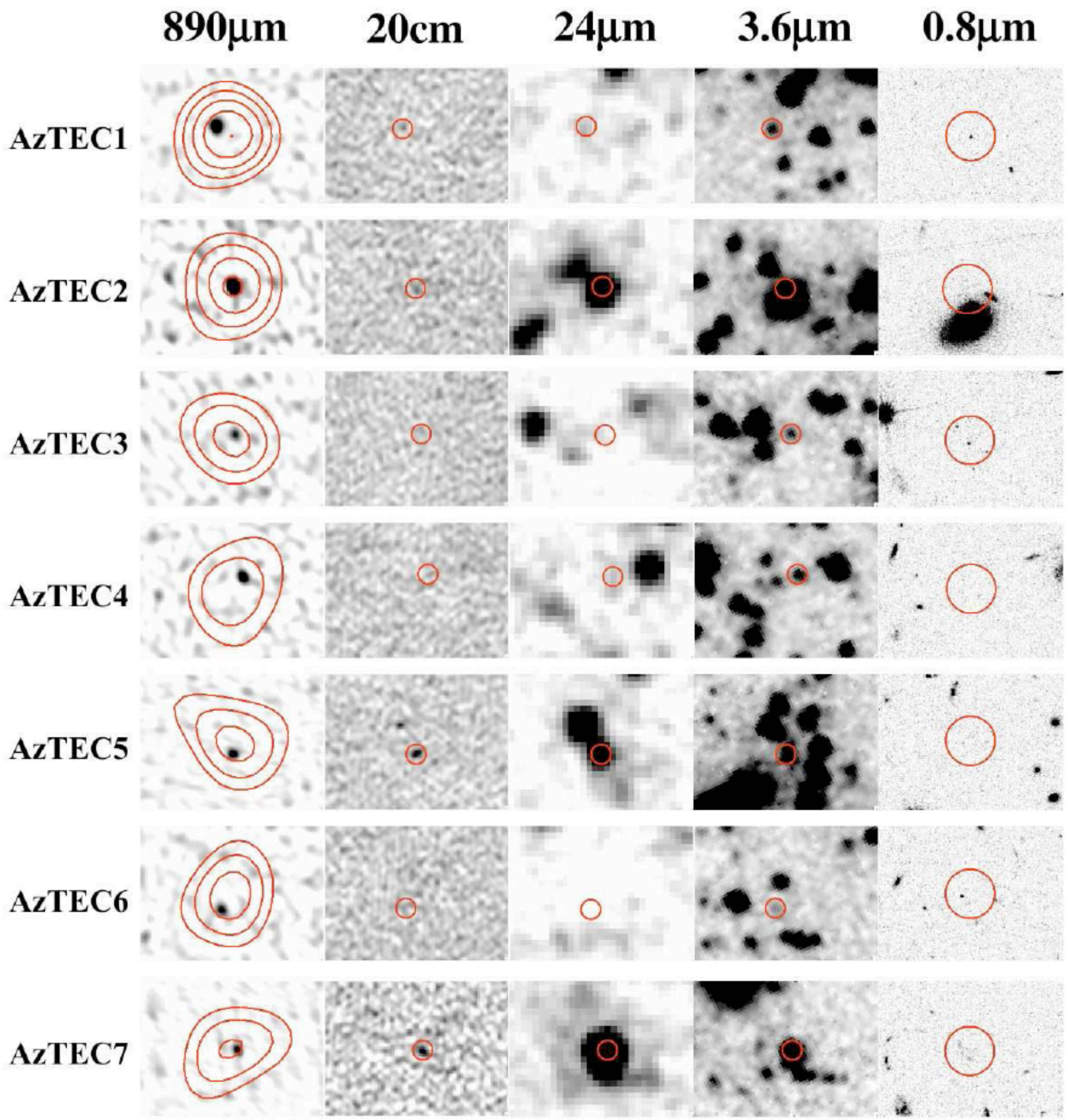


Dusty Galaxies often Lack Optical Counterparts



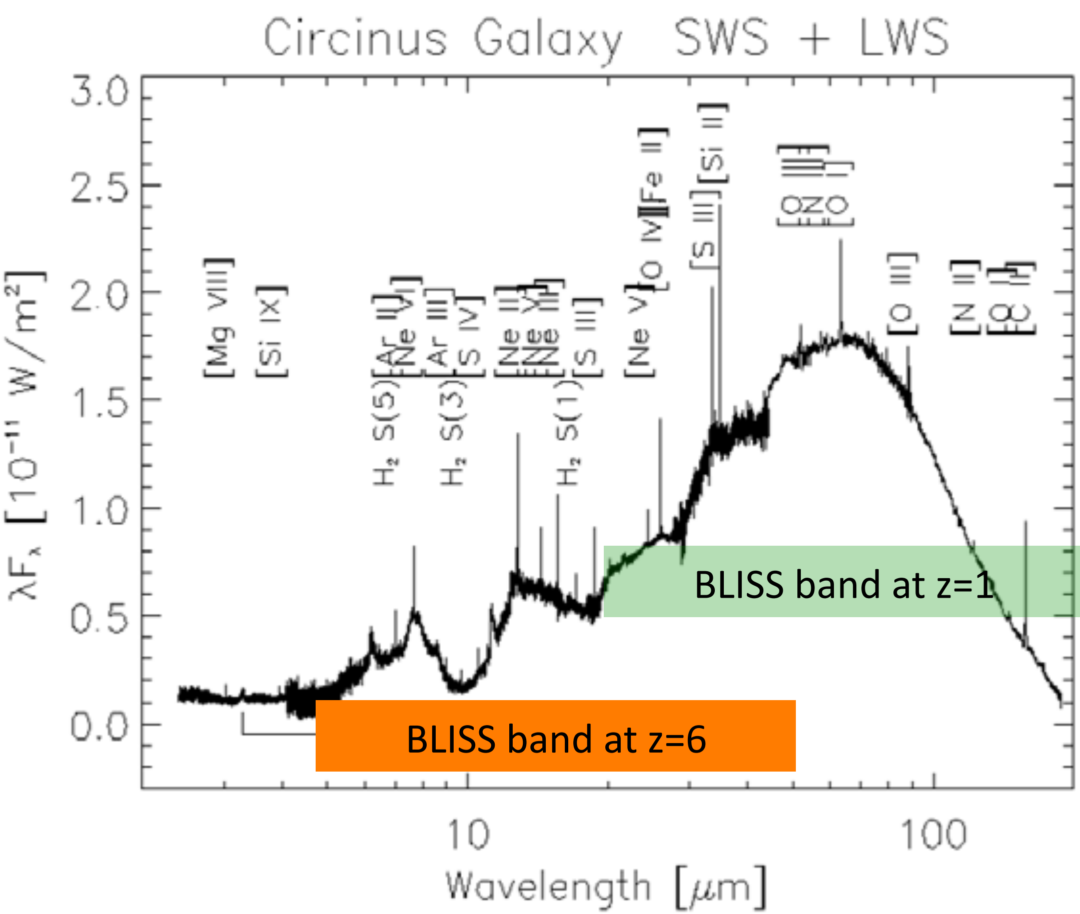
SCUBA Deep Field: Hughes et al 1998





Younger et al. 2007, AzTEC / SMA: higher z than radio-ID'd ?

THE PROMISE OF FAR-IR SPECTROSCOPY



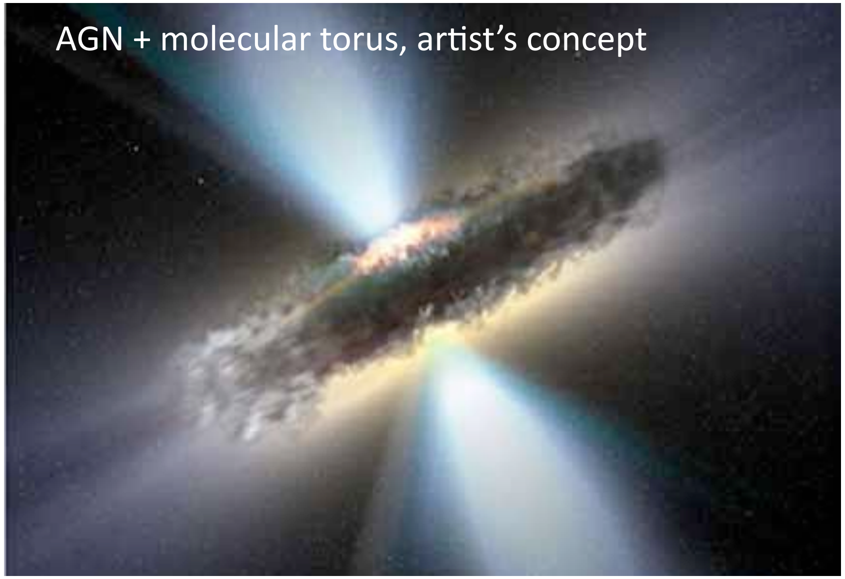
A nearby galaxy observed with the infrared Space Observatory reveals the wealth of information available. BLISS- SPICA can measure this spectrum from galaxies as they first formed when the universe was 1/10 of its present age.

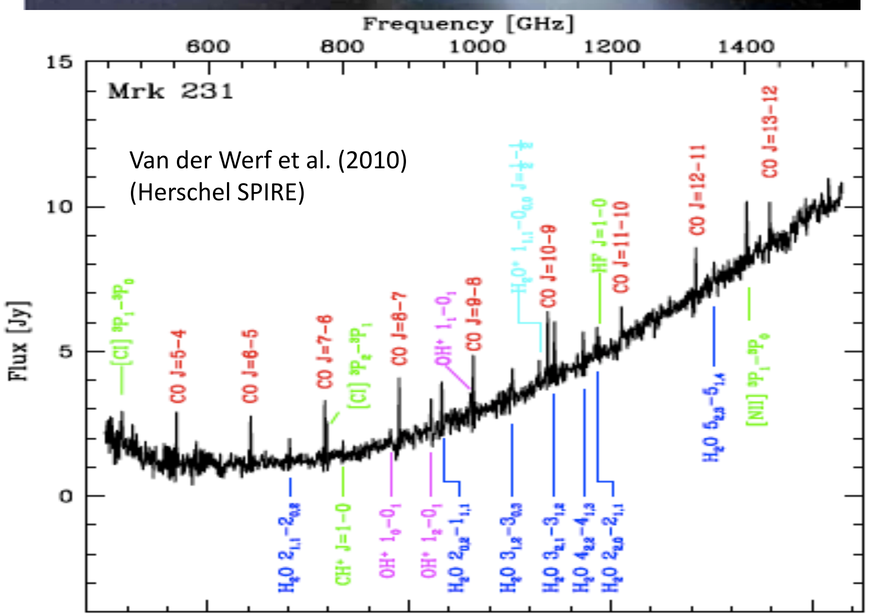
A wealth of information is available for early-universe galaxies if we have the sensitivity:

- Suite of lines provides a reliable redshift template, perhaps the only method for very dusty sources.
- Fine structure and molecular lines dominate the gas cooling and measure its properties:
    - → Gas mass, temperature, density
    - → UV field strength and hardness
    - → Metal abundances
  - → Starburst / AGN contributions
  - → Stellar type, starburst age.
  - → Degree of ISM processing

Far-IR lines are subject to very little extinction, they probe the bulk of a galaxy.

REVEALING THE BLACK-HOLE--GALAXY CONNECTION





The mid- to far-IR contains important spectral probes of black hole growth and Quasar birth.

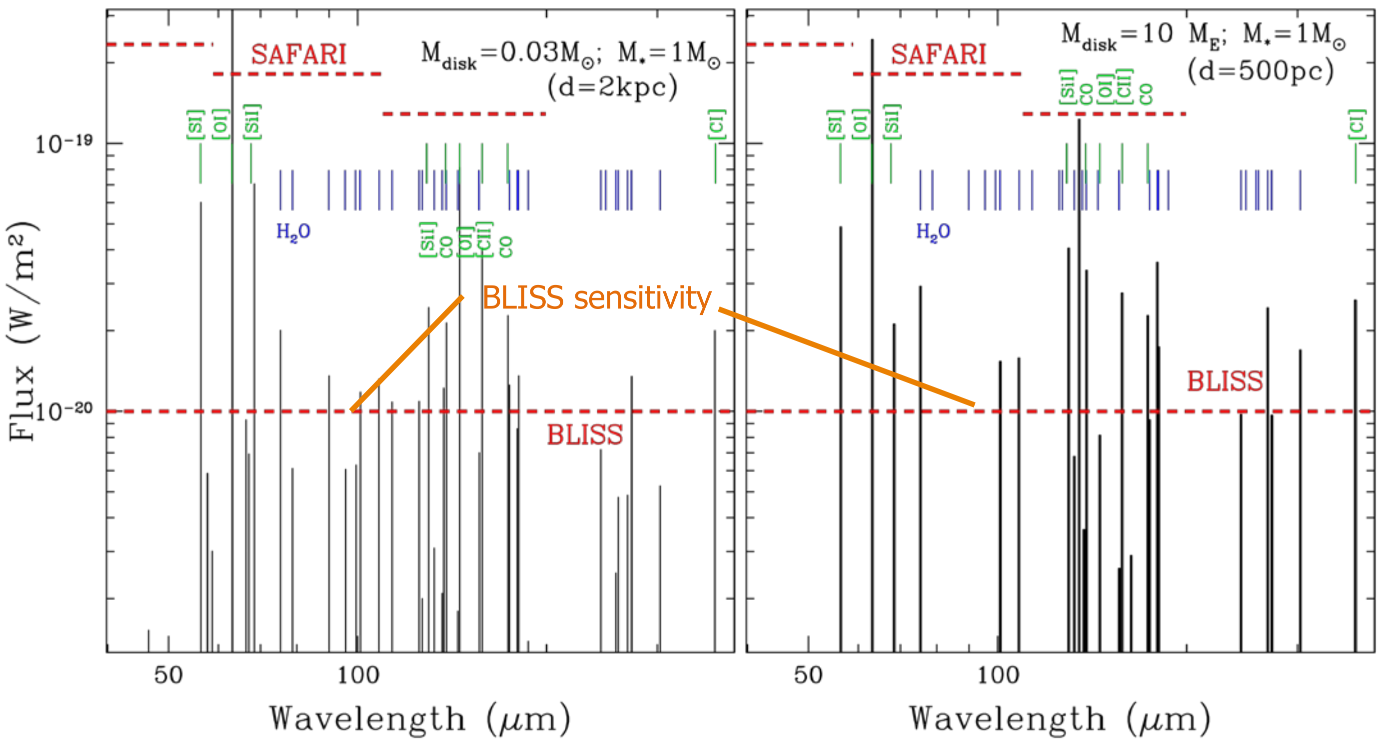
- Seyfert galaxies often show enhanced neutral gas coolants ([OI] 63 mm and [SiII] 34 mm) due to X-ray heating and jet-induced shocks. BLISS will distinguish these scenarios with a suite of far-IR lines.
- Very-high-ionization plasma around an accreting black hole is unambiguously signaled with fine-structure lines of extreme species such as Ne^{4+} and O^{3+}.
- Blueshifted molecular absorption (e.g. OH 79 mm) signals the ablation of the molecular torus and the transition from buried to naked QSO in merging galaxies.
- Warm, dense molecular gas in the putative molecular torus around an AGN should emit in the high-J CO rotational transitions, peaking around J= l_{rest}~50-80 mm and the far-infrared.

>>The SPICA/BLISS wavelength range and sensitivity is required for studying these phenomena in galaxies at the peak QSO epoch (z=2-3) and beyond.

Gas in Forming Planetary Systems

- Gas in protoplanetary disks is essential for formation of giant planets; even small amounts of residual gas at late stages can influence planetary migration and eccentricity evolution.
- Bulk of the mass in the disk is believed to lie at r≥20 AU, and is expected to cool through the far-IR atomic O and C transitions, and rotational lines of CO and H_2O.

Models convolved to R=400 (fluxes in W/m^2)   *Uma Gorti (Ames)*



The full suite of spectral lines in the modeled objects above are readily detected with SPICA/BLISS, but are very difficult or impossible with SAFARI.

SPICA/BLISS will obtain a census of the full evolutionary range, from massive primordial disks with 0.01 M_{Sun} of gas to older, evolved systems with only a few M_{Earth} of gas remaining.

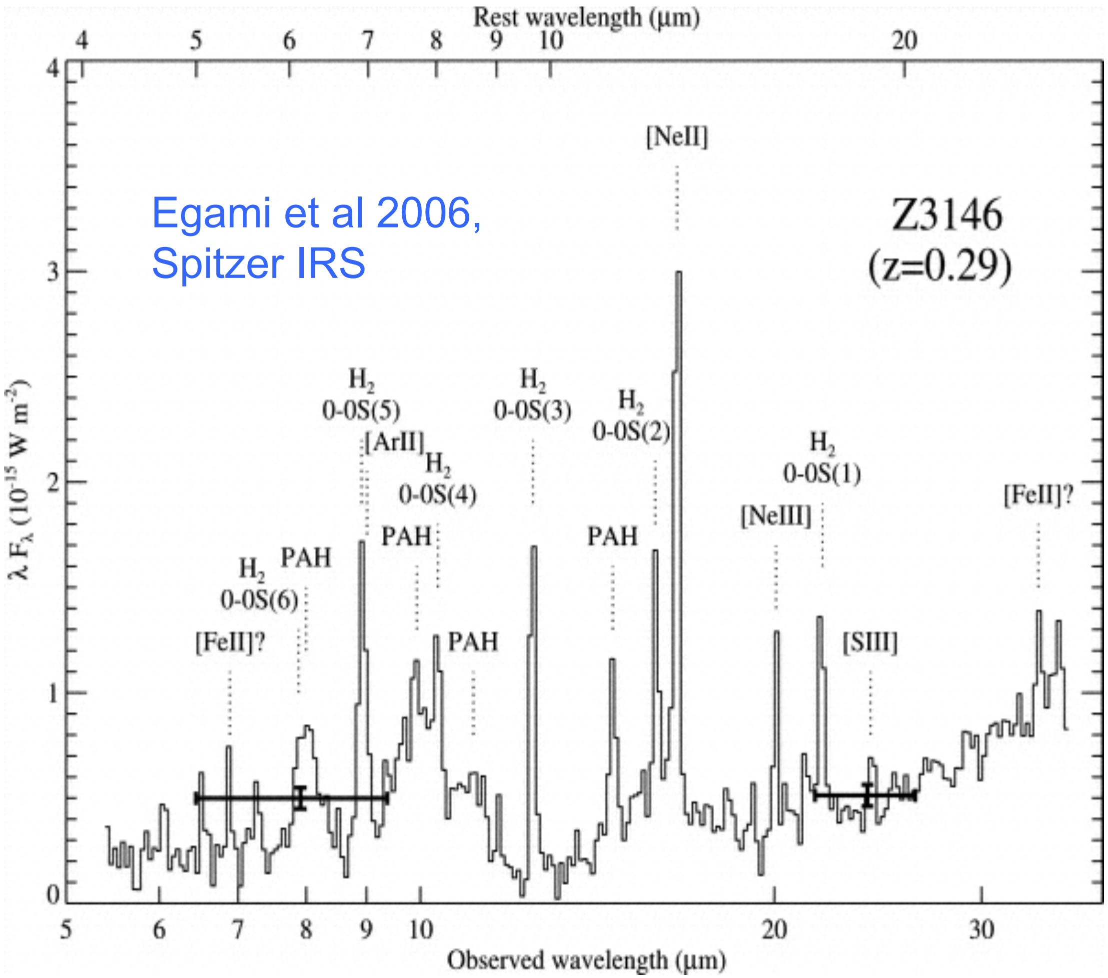
SPICA/BLISS sensitivity allows observations at kpc-distances, accessing clusters with a wide range of ages. SPICA/BLISS will measure the gas disk lifetimes directly for the first time.

Example clusters for SPICA/BLISS disk spectroscopy:

NGC 2362 (5Myr, d=1.5 kpc), NGC 6871 (10Myr,d=1.7 kpc), h-&χ-Per (13Myr, d=2.3kpc), and many more.

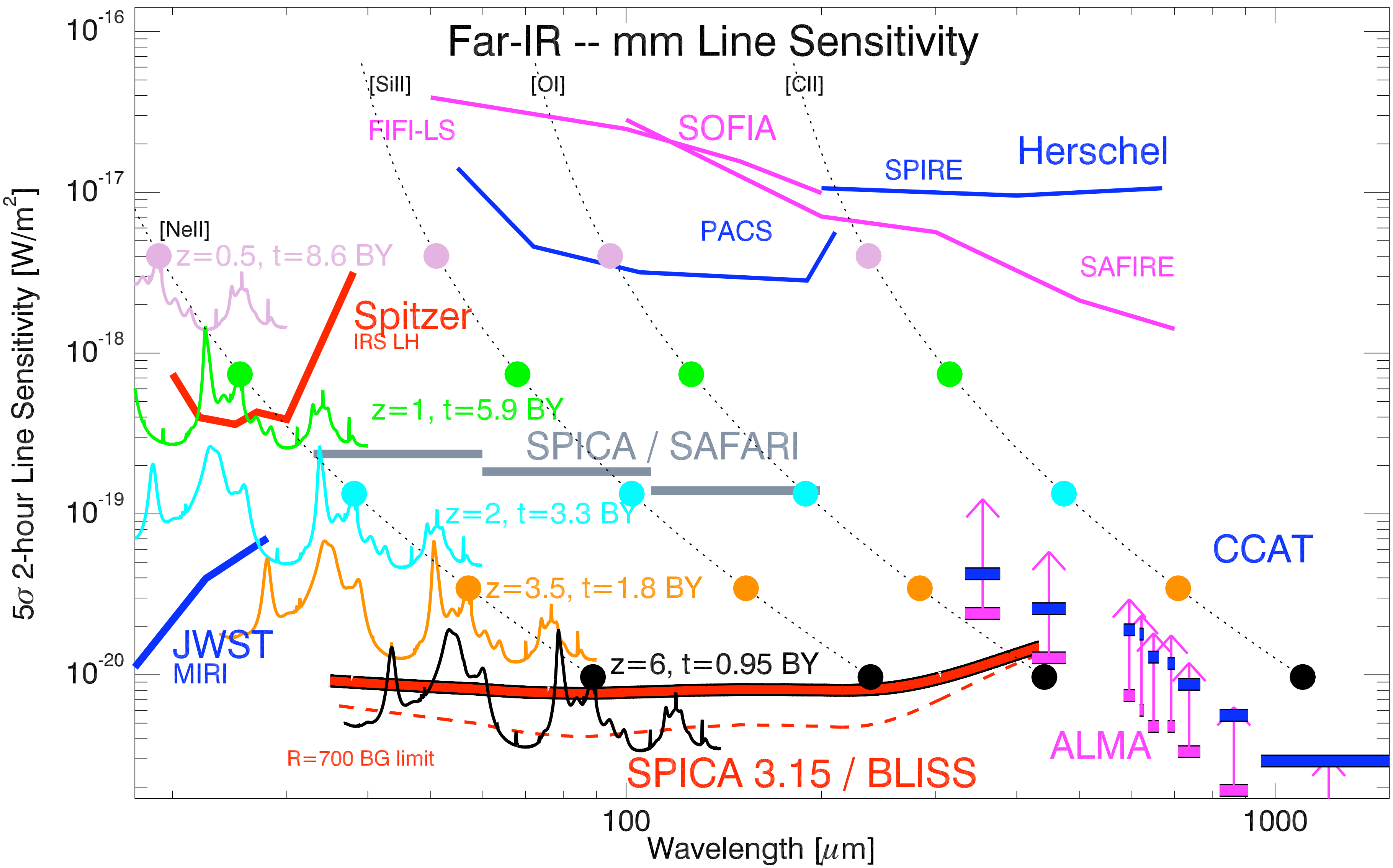
The Rise of Heavy Elements and Molecules

As primordial gas is enriched with metals from the first stars, the dominant cooling pathways shift from pure H_2 to fine-structure lines and dust features.

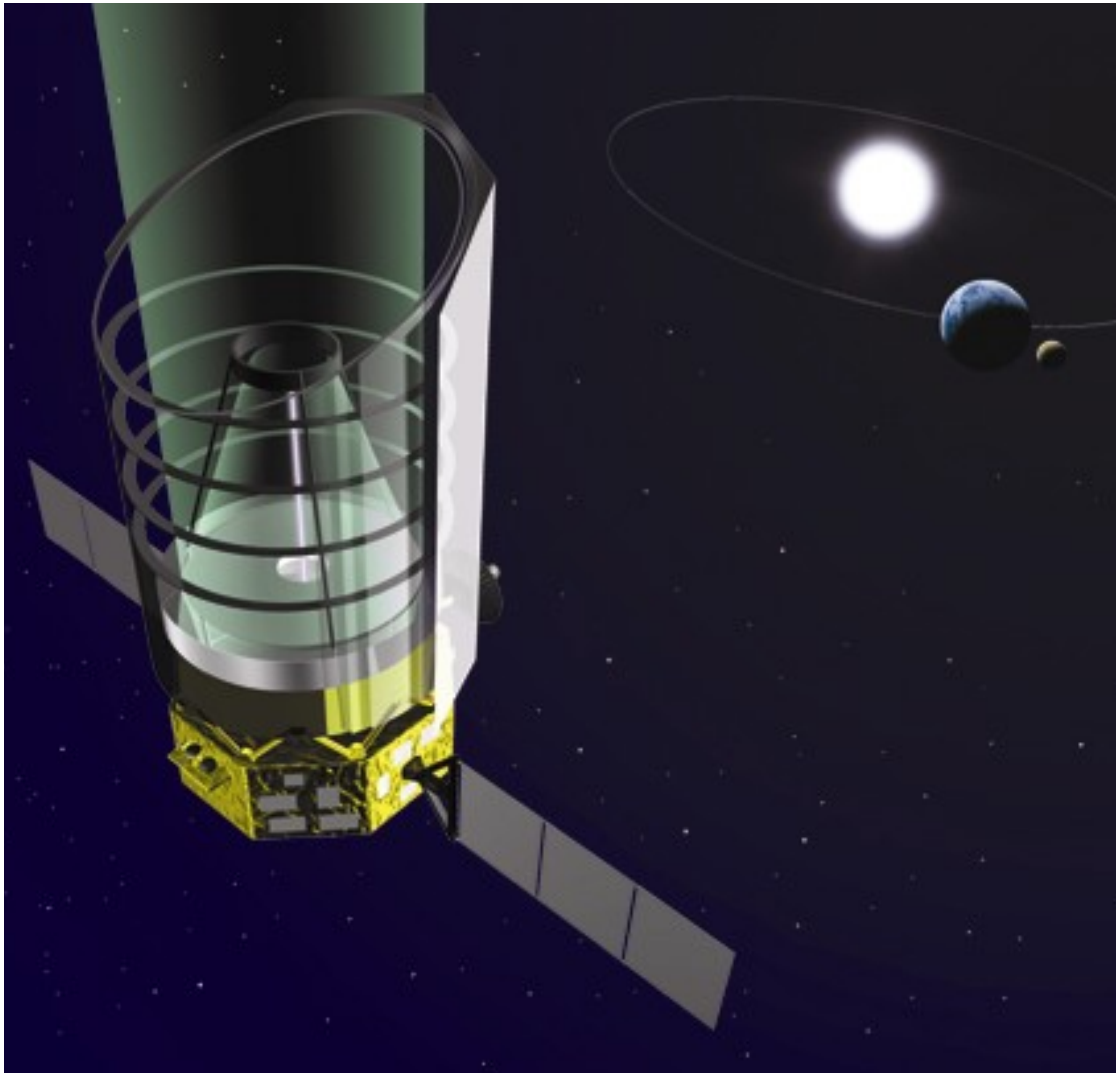


- Strong H2 emitters found in the local-Universe may be analogs of early-Universe shocks produced in galaxy formation and AGN feedback, perhaps as element enrichment is taking place. This Zw3146 BCG spectrum would be detectable at z=8-10 with BLISS / SPICA!
- As they arise, PAH features become important ISM coolants. Their Large equivalent widths may offer the best probe of heavy metal abundance at early times. While not accessible to JWST or ALMA, SPICA-BLISS can readily detect the PAH emission from galaxies systems at z>6, as they come to be.

BLISS Designed for Deep Follow-Up Spectroscopy



SPICA -- The First Large Cryogenic Observatory



Space Infrared Telescope for Cosmology and Astrophysics
Takao Nakagawa, PI

- COOLED Telescope
  - Optimized for Thermal IR (10-600 μm)
  - Complementary with JWST, ALMA
- **Size:** 3.2 m (No Deployment)
- **Temperature:** <6 K
  Stirling + J-T closed cycle
- **Facility heat lift at 1.7 K:** 10 mW
- **Orbit:** L2 Halo
- **Lifetime:** 5 years +
- **Launch:** ~2019 by HIIA-202

A major international mission

European consortium developing SAFARI (SRON lead) and telescope (ESA)

Focal plane instrument definition and allocations underway now.

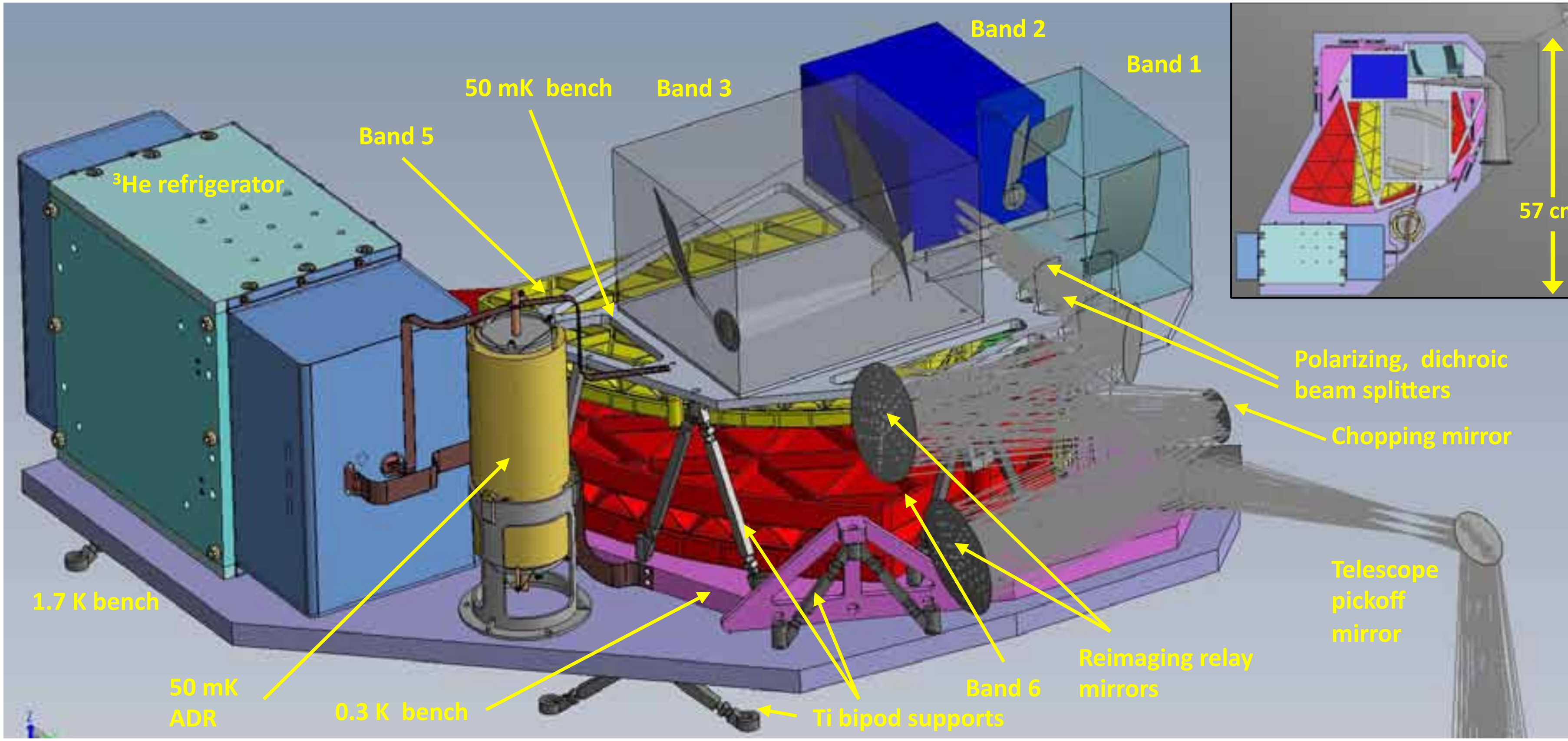
BLISS for SPICA is a US Far-IR Community Goal, Recommended by Astro2010 Decadal Survey

Table B.1 Summary of Priority Activities as Recommended by the Program Prioritization Panels.

EOS Project	Program Cost Appraisal (category)	PAG Project	Program Cost Appraisal (category)	RMS Project	Program Cost Appraisal (category)	OIR Project	Program Cost Appraisal (category)
(1) WFIRST	$1.5B (L)	(1) LISA	$1.5B (L)	(1) HERA-I and HERA-II	$25M + $85M (M)	(1) GSMT	≥$1B (L)
(2) IXO (project start)	$1.0B (L)	(2) ACTA (AGIS)	$0.2B (L)	(2) FASR (2) CCAT	$100M (M) $110M (M)	(2) LSST	$460M (L)
(3) Exoplanet Mission	$0.7B (L)	(1) Pulsar Timing Array for Gravitational Wave Detection	$70M (M)	ATA Enhancement	$44M (M)	(1) Mid-scale NSF program augmentation (OIR+PAG+RMS)	$200M
(1) BLISS	$0.2B (M)	(1) NASA Explorer Augmentation	$1B (M)	Enhancements to GBT, EVLA, VLBA, ALMA, Enhancements to CARMA, EHT	$120M $25M	(2) TSIP augmentation	$40M (M)
(2) Explorer	$0.5B (M)	(2) Technology development augmentation and ULDB R&D and augmentation	$550M NASA (M), $150M NSF+DOE (M)	---	---	(2) OIR System augmentation	$61M (M)
(3) R&A	$0.2B (M)	(3) Auger North	$60M (US portion) (M)	---	---	Small, unprioritized programs	$100M

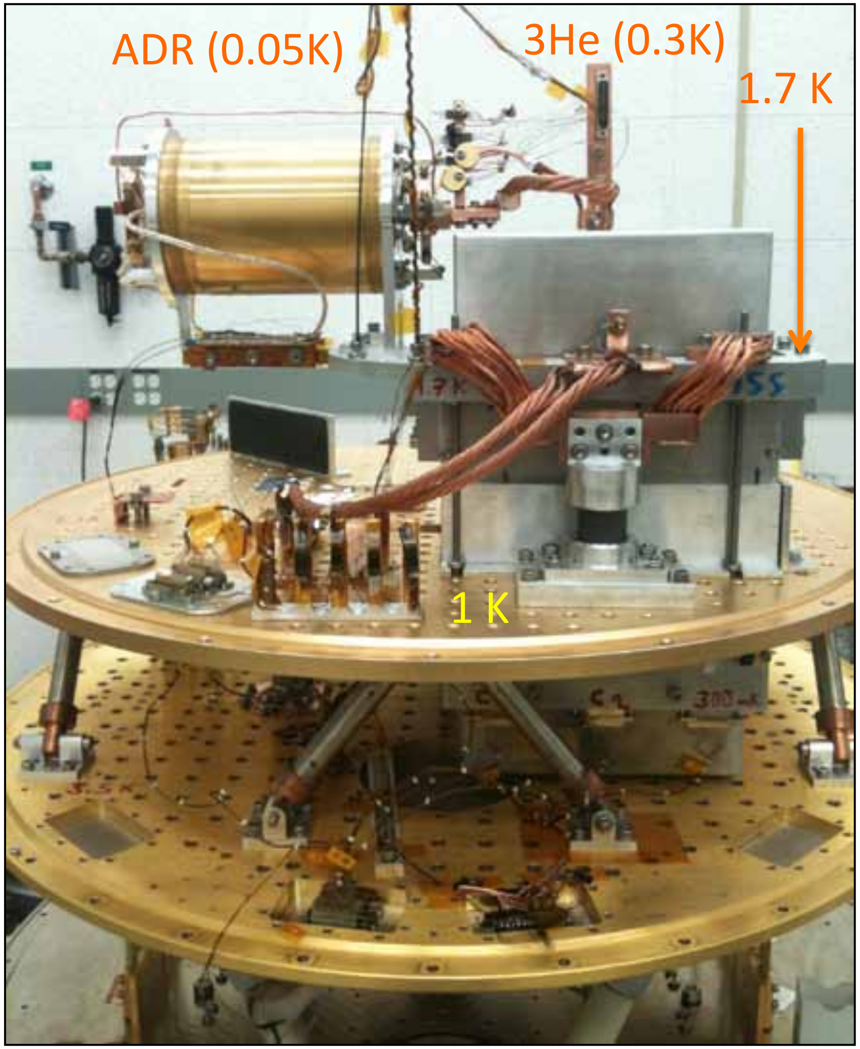
NOTE: Entries under each panel are in priority order within size category. Note that the RMS panel has two second equal priorities. The EOS costs are shown for the panel's enhanced budget scenario. The tabulated costs are in FY2010 dollars and are estimates for the decade.

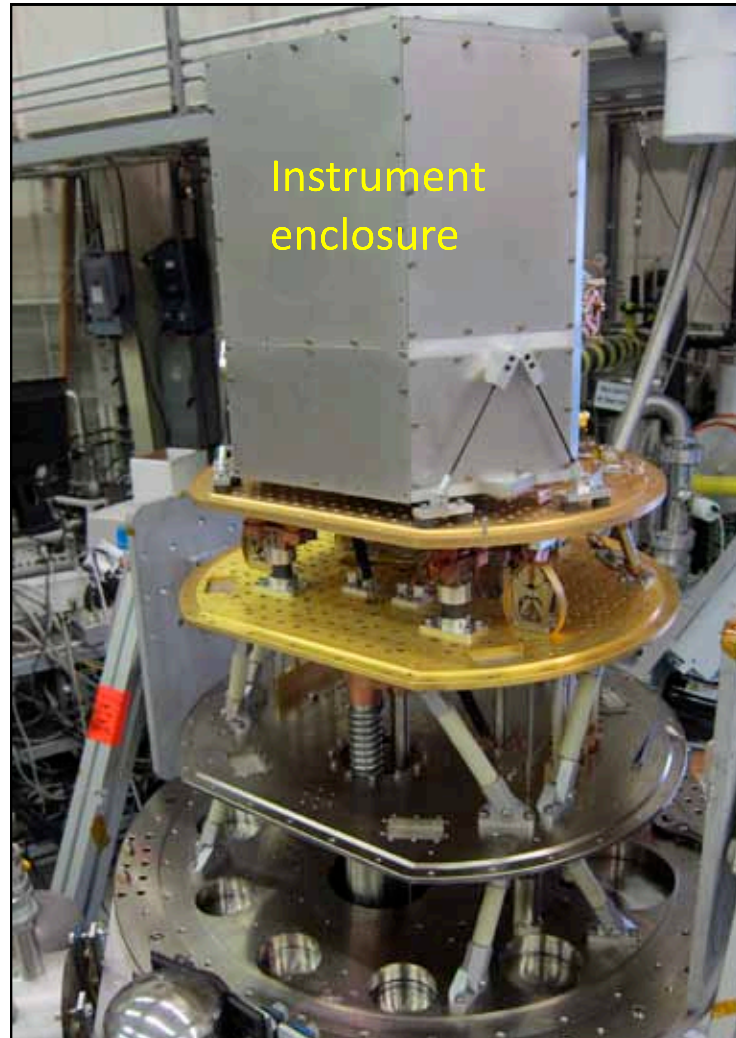
BLISS Instrument Concept



- Goal: measure a galaxy's full spectrum from 35-433 microns simultaneously.
- 6 bands, each with **two R>400** broadband grating modules (12 total)
- **4224** superconducting bolometers with time-domain SQUID MUX
- Assembly cooled to 50 mK with a **2-stage magnetic + 3He sorption refrigerator**, supported with a titanium suspension.
- Bolt and go, no moving parts except for chopping mirror in feed optics.
- **Specs**: 50x50x40 cm^3, **30 kg** (cold). JPL cost ~$150M

BLISS 50 mK COOLER-> PROTOTYPE AT JPL

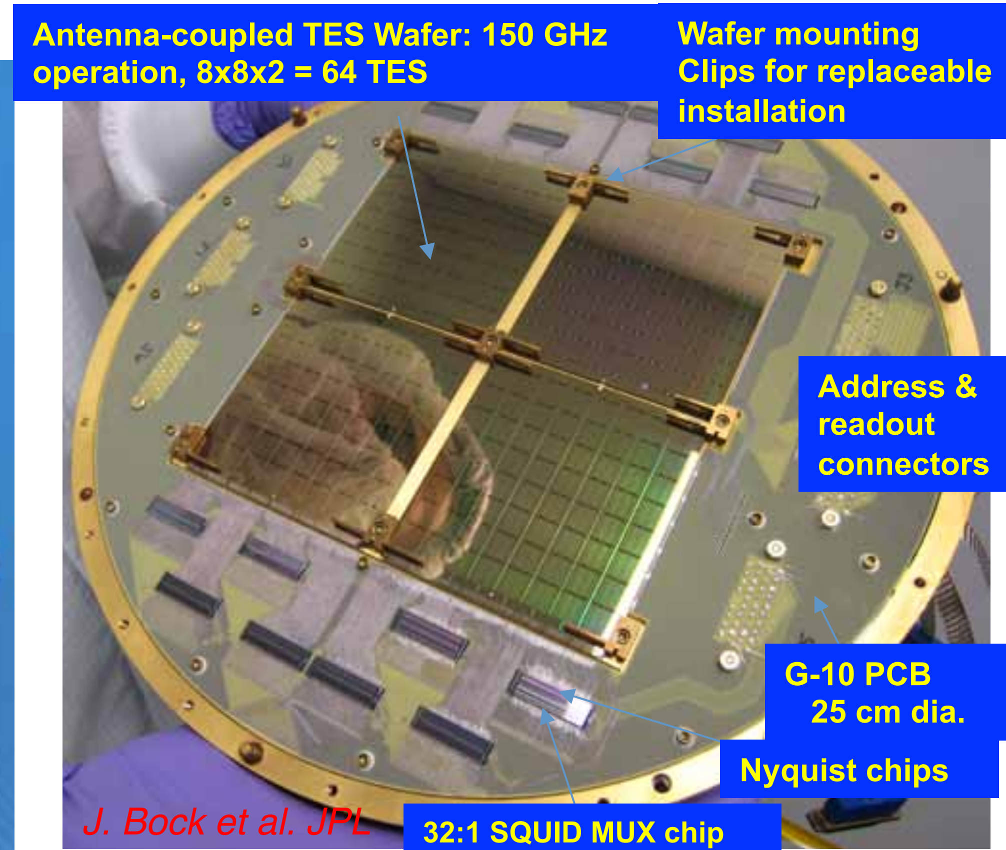




- Regulated 1.7 K and 4.5 K stages mimic SPICA heat lift points, allows demonstration of target heat dump.
- Large instrument volume allows realistic thermal ballast, e.g. 5 kg of aluminum.
- Continuous operation at 300 mK and automated ADR cycling demonstrated ***at SPICA lift allocations***. T. Prouve (JPL)

UNIQUE US CAPABILITIES FOR SPICA

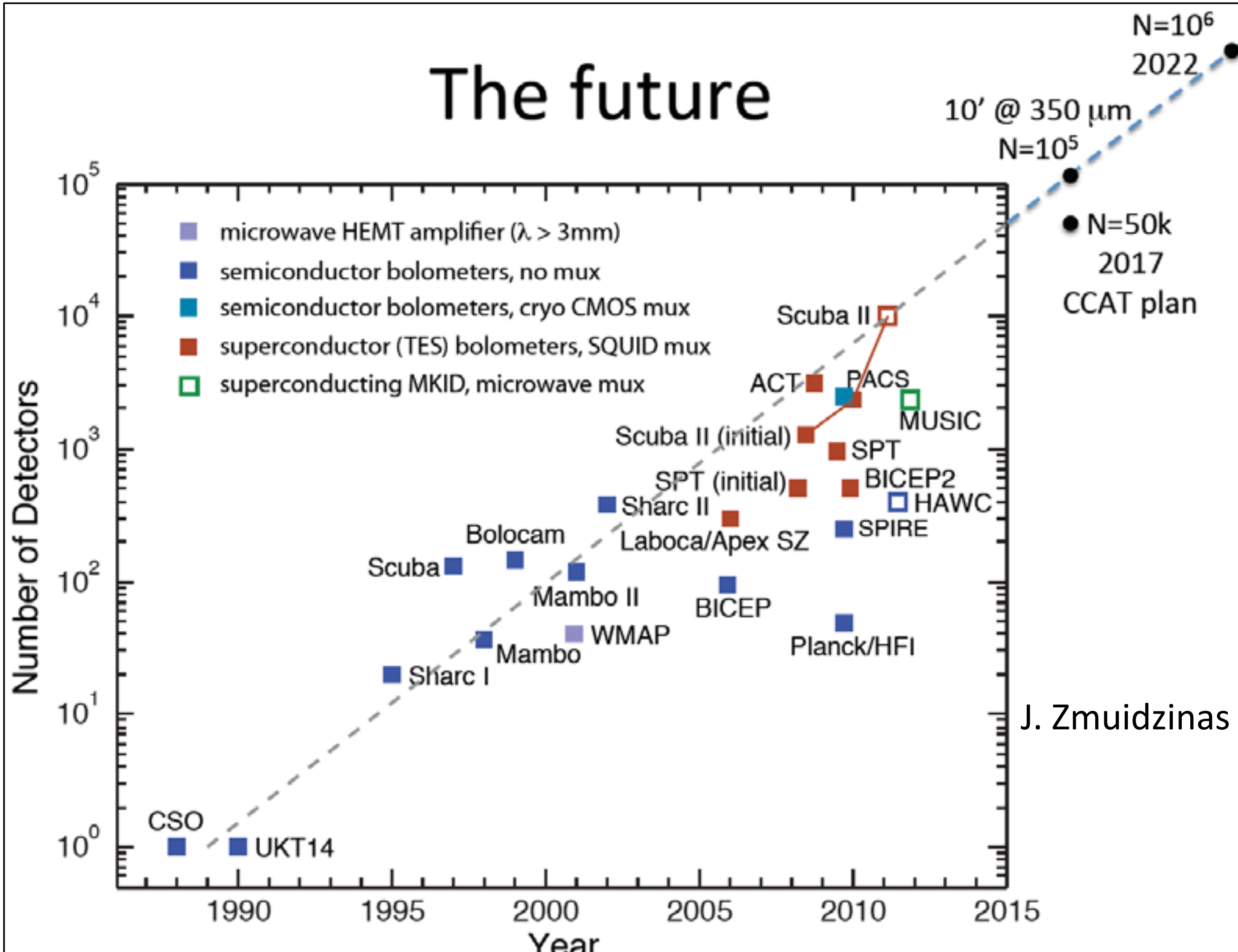
Far-IR bolometers arrays -- the heart of an instrument.
Progressing from semiconducting → to multiplexed superconducting



Delivered for flight -> Herschel and Planck
- individually read-out devices
  - 384 total bolometers for SPIRE
- semiconducting thermistors

Being fielded in ground-based, balloon-borne instruments
- kilo-pixel arrays, e.g. SCUBA-2, 10,000 pixels
- superconducting thermistors
- enables ultra-sensitive bolometers for BLISS

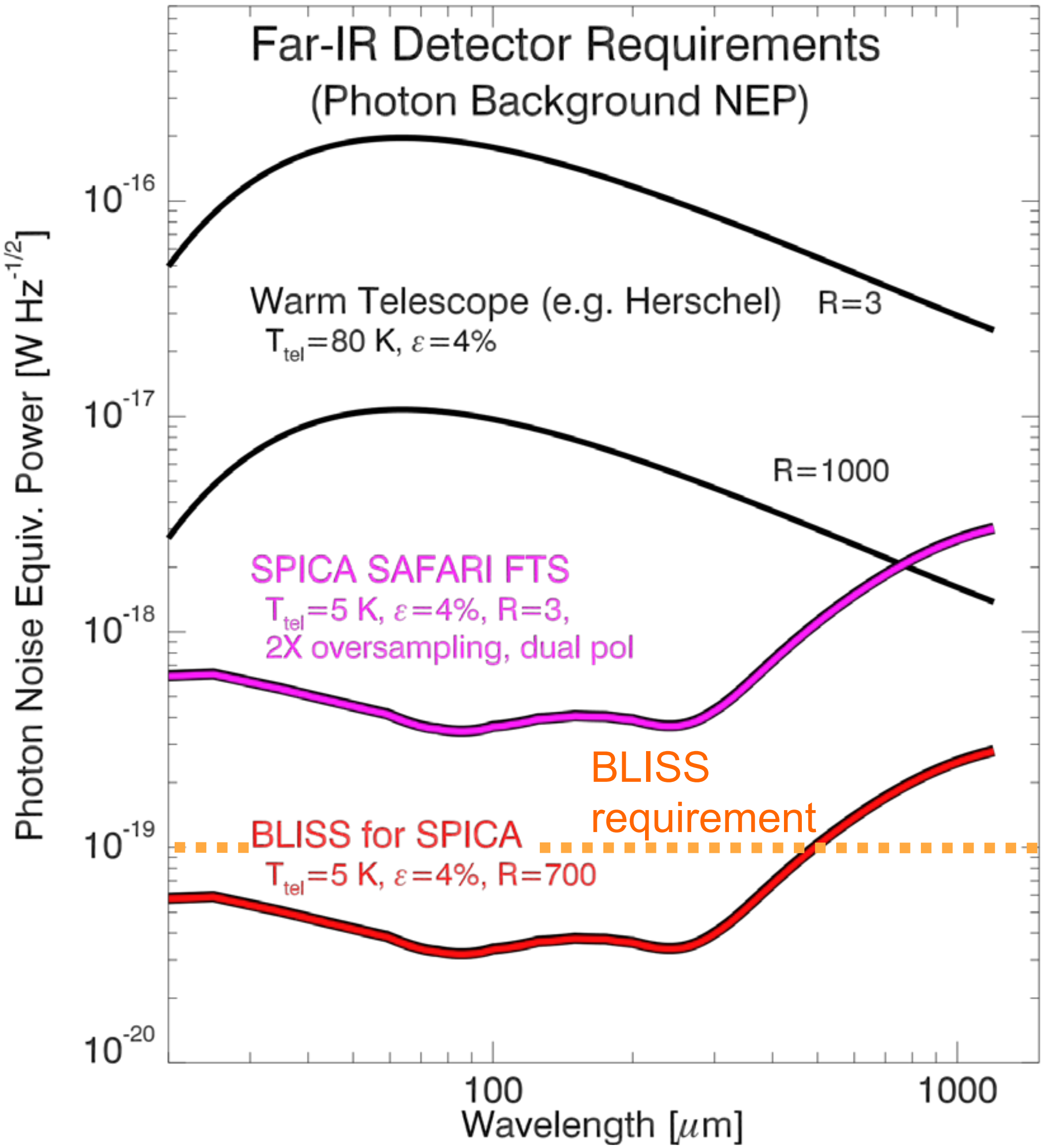
Growth in Far-IR Direct Detector Formats



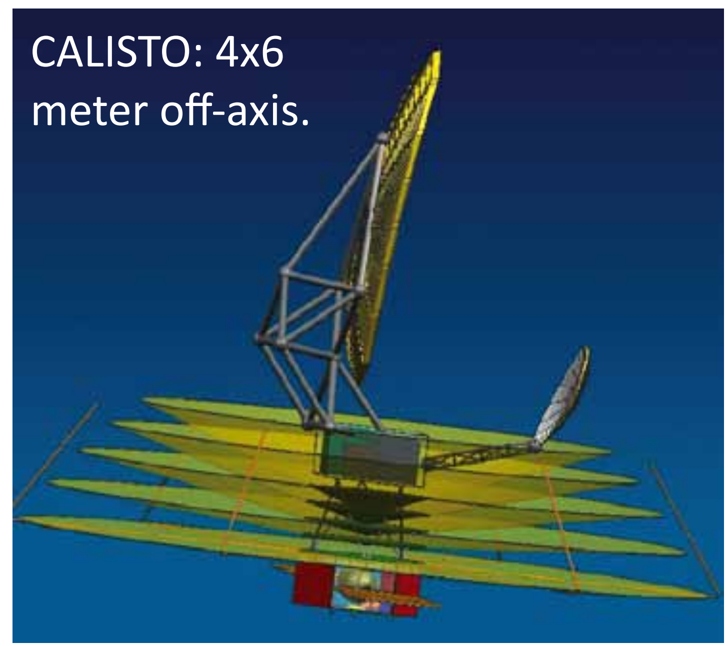
10^5 pixels in a decade, if we can afford them -> MKIDs offer low-cost multiplexing

BLISS Sensitivity Requirements

BLISS requires sensitive devices, paves the way for future missions

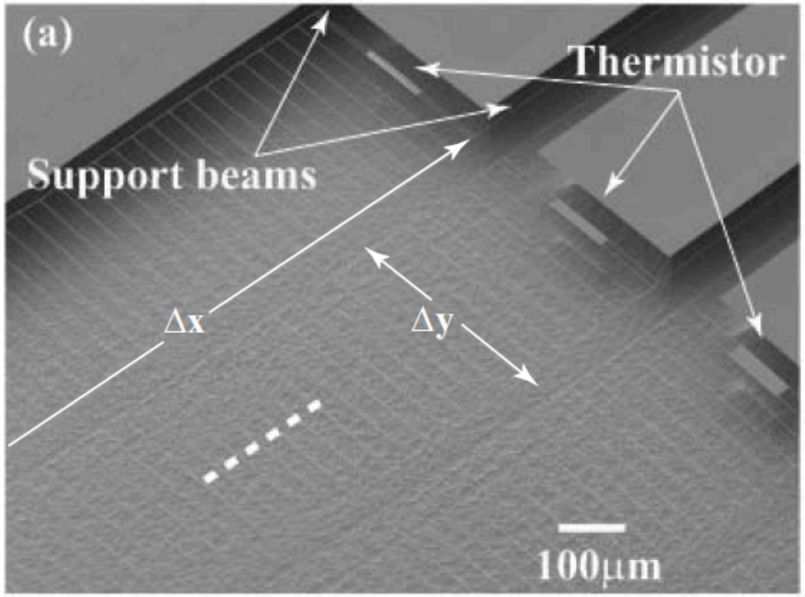


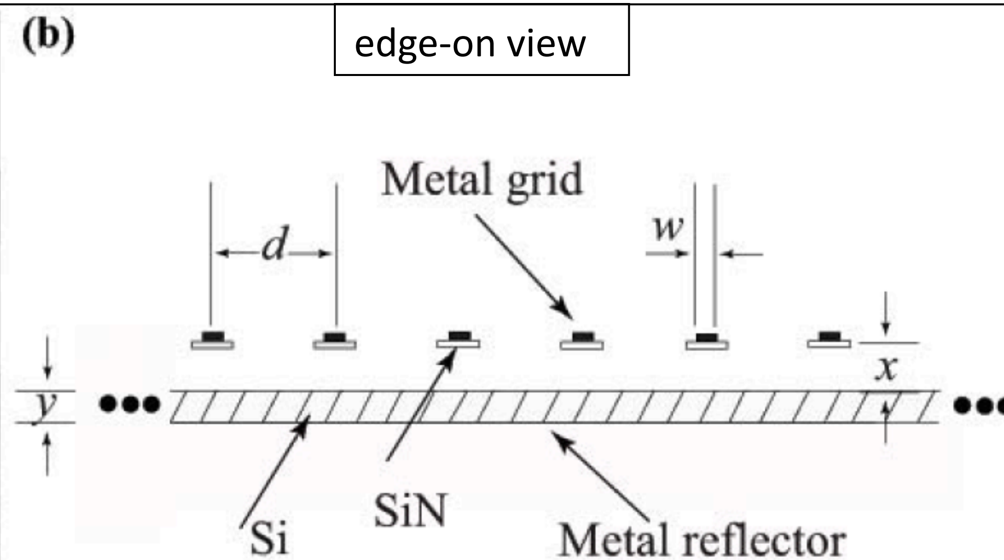
- Future Far-IR detectors must be more sensitive than anything yet flown.
- Ultimate limit is the zodiacal+Galactic dust emission, and the telescope & CMB at 300 μm and longer.
- There is no terrestrial or sub-orbital platform to field these detectors. Even Herschel has backgrounds 10,000 times too high.
- SPICA & BLISS paves the way for future far-IR spaceborne instruments.



BLISS Bolometer Approach

50 mK TES Bolometers Arrayed in 1-D





- Silicon nitride micro-mesh approach (here single polarization) with quarter-wave backshort.
  - Low-stress silicon nitride -> devices flat to a few microns.
- Absorber: 2 mm by 300 μm (for example), and single polarization. Gold bars thermalize along length.
- Isolation legs: e.g. 1 mm x 0.4 μm by 0.25 μm, produces G which meets BLISS requirements.
- XF_2 etch undercuts front side on double SOI (silicon-on-insulator) wafer
  - Also investigating a wet-release process which appears to reduce heat capacity.
- MoAu bi-layer TES (fraction of a square), aluminum or niobium leads.
  - Operating impedance 3 milli-Ohms.
  - Plan to use a second TES in series which will enable a large dynamic range and facilitate observation of even bright Galactic targets—elemental titanium at 450 mK.

BLISS DETECTOR PROGRESS:

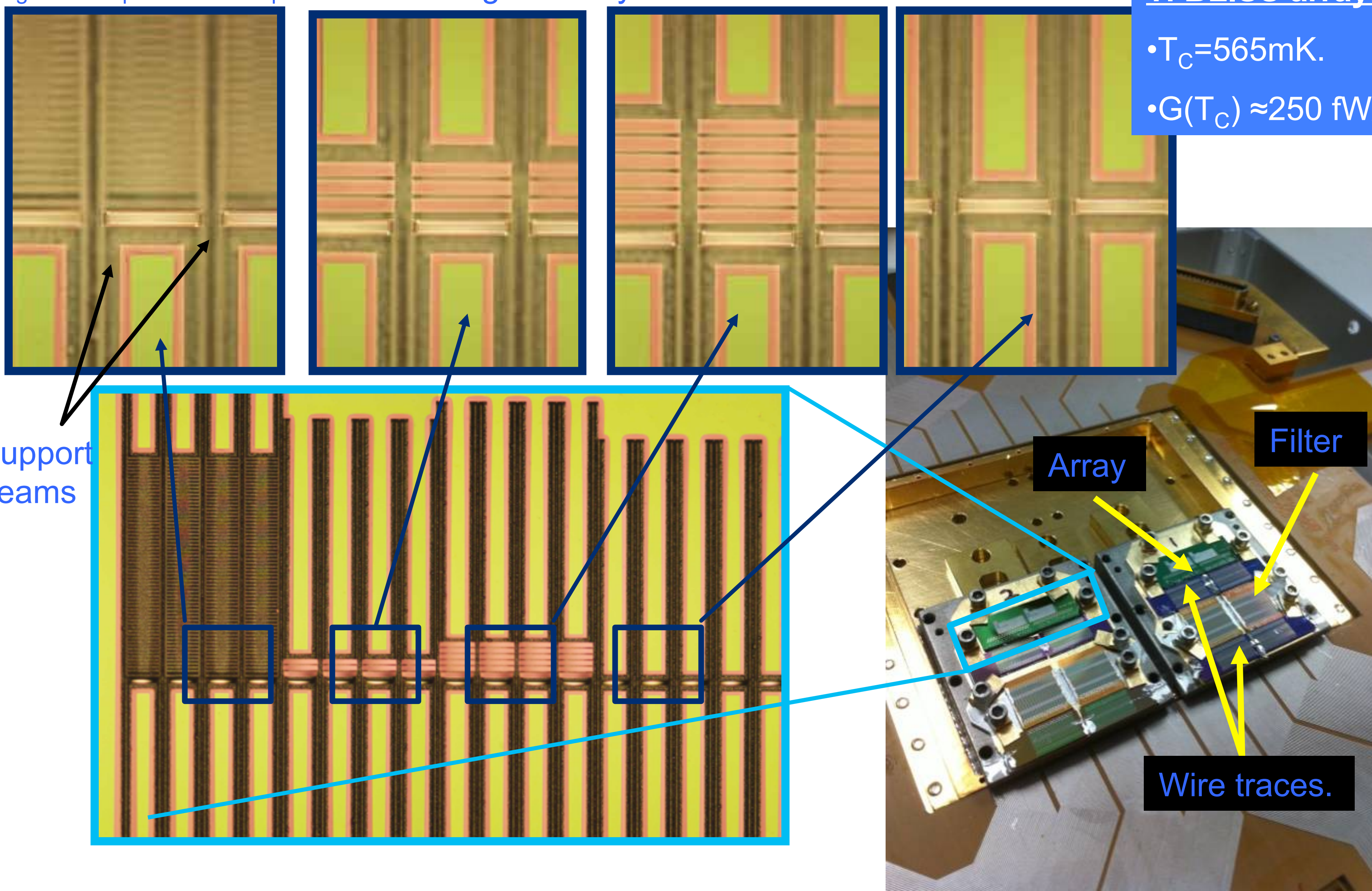
TITANIUM BLISS TEST ARRAYS IN MUX

Ti BLISS arrays

- T_C=565mK.
- $G(T_C) \approx$250 fW/K

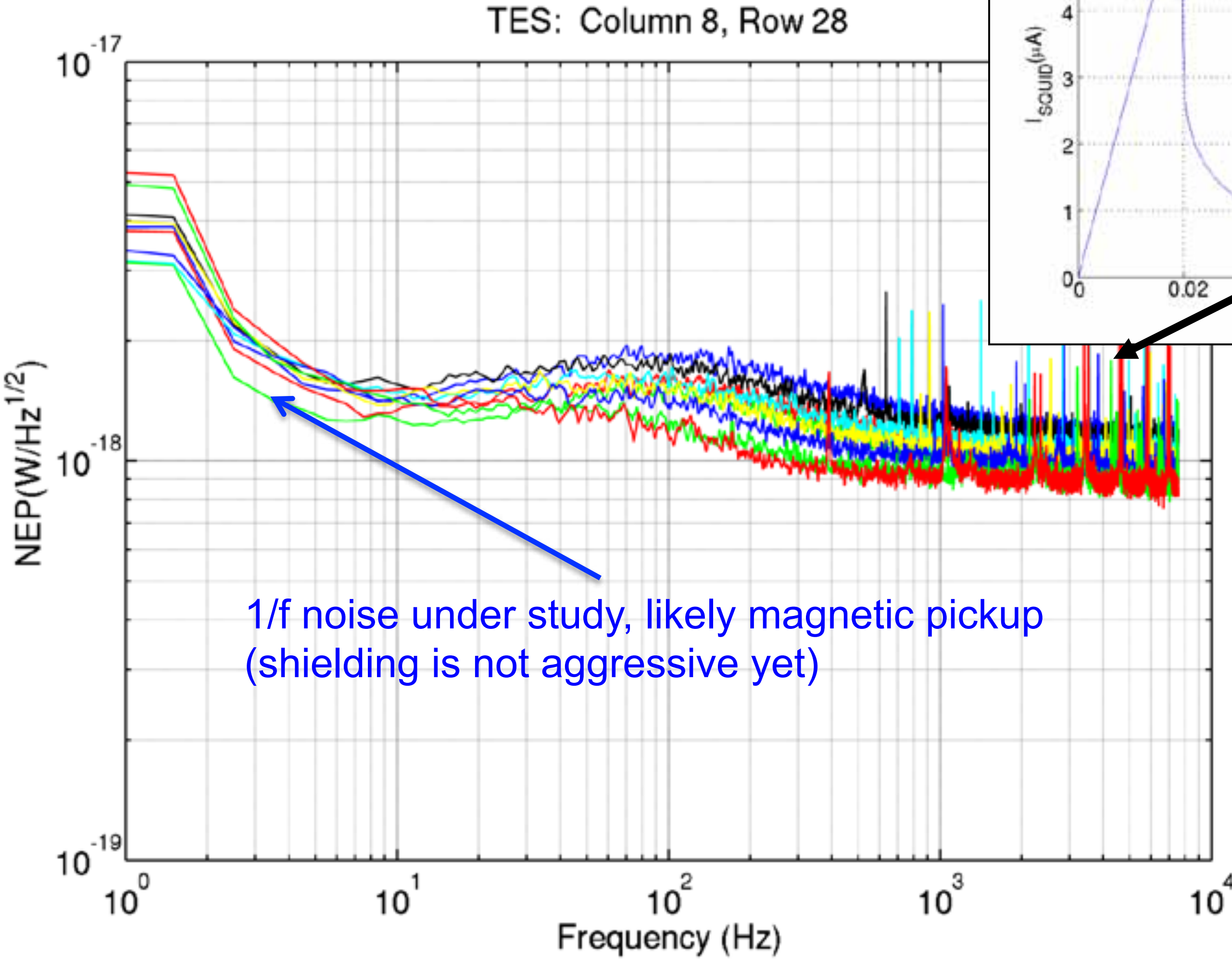
Images from optical microscope.

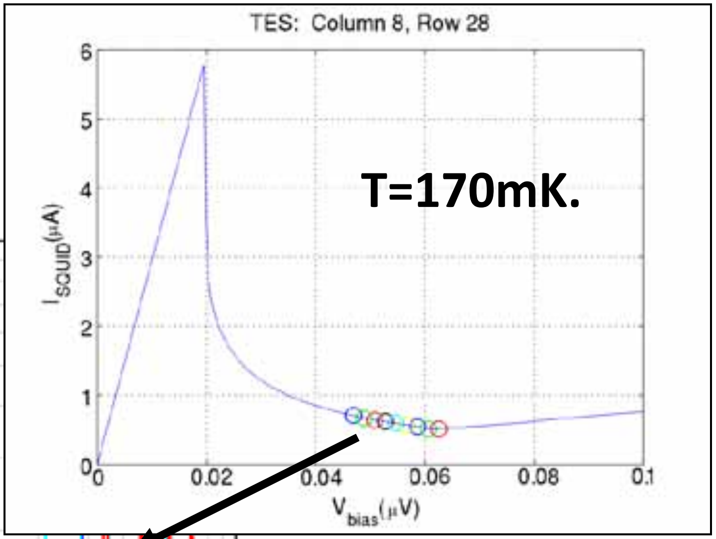
Testing a variety of absorbers:



Ti BLISS Test Array: NEP w/ MUX is as designed (A new world record for the SQUID MUX!)

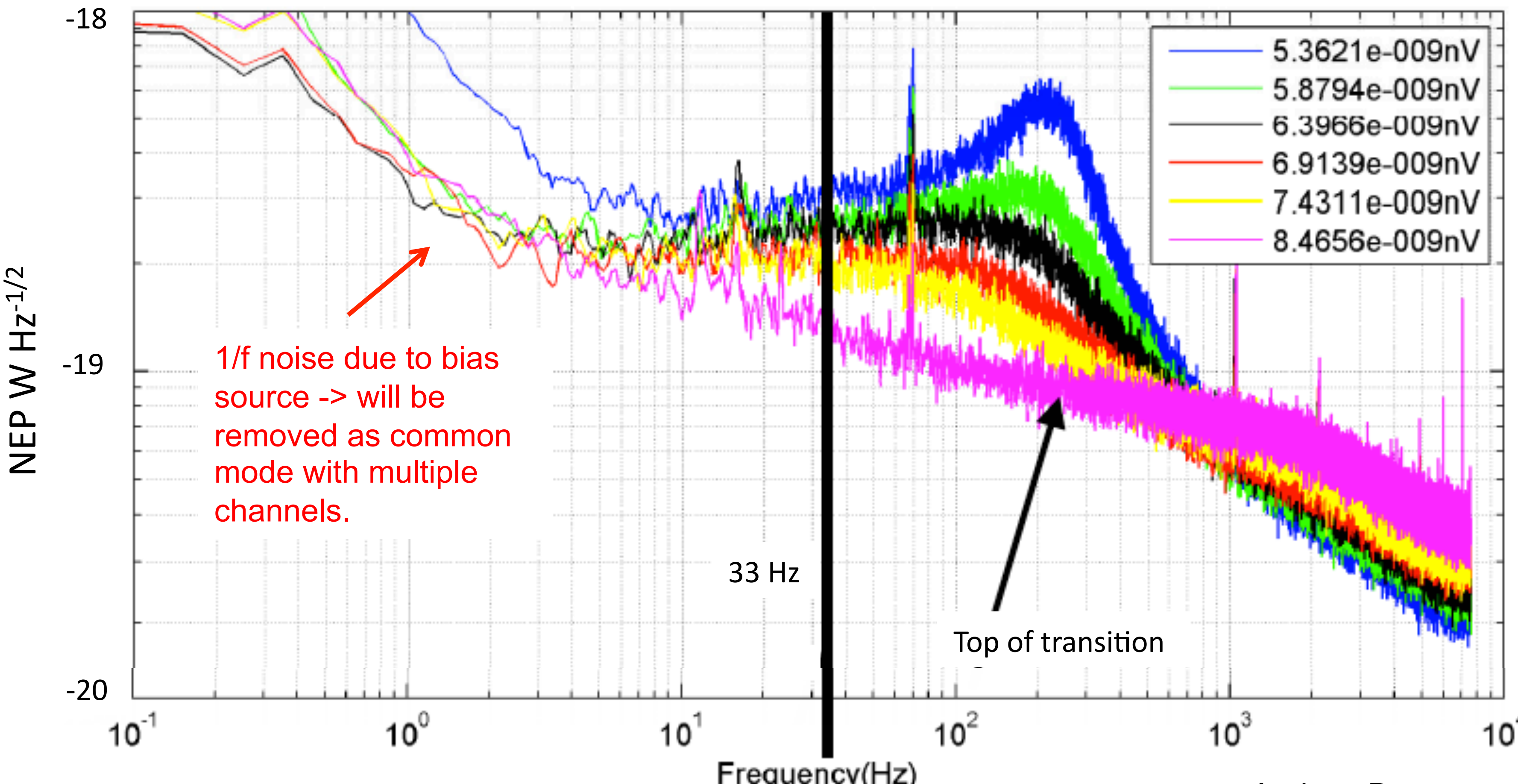
NEP: 1.5×10^{-18} W/Hz$^{1/2}$ for T_C=565mK.





Andrew Beyer
Matt Kenyon
Talso Chui
Warren Holmes
(JPL)

MEASUREMENT WITH IR DEVICE AT 150 MK
(ANOTHER WORLD RECORD FOR THE SQUID MUX)



NEP: ~2×10^{-19} W/Hz$^{1/2}$ for T_C=150 mK.

65 mK tests underway now, expect below 1e-19

Still much work to prepare for flight -> Origins technology program

Andrew Beyer,
Matt Kenyon,
Pierre Echternach,
Warren Holmes,
Talso Chui (JPL)

BLISS U.S. Study Team

Technology & Engineering Team	Role
Matt Bradford	PI, Spectrometer design
Matt Kenyon	High-sensitivity TES bolometers (JPL)
Andrew Beyer	Bolometer array characterization (JPL)
Thomas Prouve	Sub-K refrigerators (JPL)
Jamie Bock	Detector systems (JPL)
Warren Holmes	Thermal systems (JPL)
Kent Irwin	SQUID multiplexing and readouts (NIST)

Science Team	Institution
Phil Appleton	IPAC SSC
Lee Armus	IPAC SSC
Daniel Dale	U. Wyoming
Eiichi Egami	U. Arizona
Jason Glenn	U. Colorado
Uma Gorti	UC Berkeley / NASA Ames
Martin Harwit	Cornell (Emeritus)
George Helou	IPAC
Dan Lester	U. Texas
Matt Malkan	UCLA
George Rieke	U. Arizona
John-David Smith	U. Toledo
Gordon Stacey	Cornell
Mike Werner	JPL